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Opportunities for reducing turbulent skin friction drag: modeling the canonical turbulent boundary layer

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ABSTRACT

Practical schemes for the reduction of skin friction in turbulent wall shear flows have proved elusive despite decades of research. The advent of MEMs technology promised the opportunity to sense and control individual high skin-friction events on the wall beneath a turbulent boundary layer, but issues of robustness, spatial resolution and the fundamental question of a suitable low-order model of the boundary layer for *control* rather than *manipulation* have hindered progress in this area. However recent insights into coherent structure in turbulent boundary layers have hinted at the possibility of novel approaches to both modeling and control.

Over the past decade, the generation of instantaneous spatial velocity information permitted by advances in Particle Image Velocimetry has permitted the description of the behavior of a canonical Zero Pressure Gradient Turbulent Boundary Layer (ZPG TBL) in terms of the formation of long (of the order of the boundary layer thickness, δ), streamwise-aligned packets of hairpin vortices, accompanied by wall-normal zones of approximately uniform momentum and finite temporal/streamwise extent, e.g. [1]. Simultaneously, there has been mounting evidence from point measurements of *very* large scale structure, O(10δ), in the streamwise velocity. Figure 1 [4] shows the power spectral density of the streamwise turbulent velocity at the outer edge of the mean velocity overlap region $y/\delta = 0.1$ (where y is the wall-normal location and here $\delta = R$, the radius) in pipe flow, premultiplied by the wavenumber k (the logarithmic scale implies that equal area corresponds to equal energy) and normalized using the friction velocity, $u_\tau = \sqrt{\tau_w/\rho}$ (τ_w is the wall shear stress and ρ is the density). The lefthand peak occurs at $ky \approx 0.06$ which corresponds to wavelengths of ten times the boundary layer thickness: wavelengths of this order contain the majority of the energy at this wall-normal location as the Reynolds number (defined on the bulk velocity $\overline{U}$, pipe diameter D and kinematic viscosity ν), $Re_D = \overline{U}D/\nu$, increases. It has been suggested that these long motions correspond to a collection of aligned hairpin packets.

It has also been shown through single point measurements [2,3] that the very large scales “modulate” the smaller-scale turbulence activity. Figure 2 shows recent results from a study of the streamwise velocity in the near-neutral atmospheric surface layer (the highest terrestrially-achievable Reynolds number boundary layer, and at least a model for the canonical flow case) obtained using a synchronous wall-normal array of single hot-wires [5]. Simple low- (left) and high-pass (right) filters on the instantaneous

velocity traces reveal the extent of the wall-normal correlation of the very low frequency/long wavelength negative excursions in the velocity across the field of view (the bottom 5m of the surface layer of approximate thickness $50 - 100$m) and the corresponding suppression of high-frequency turbulence activity.

These structural flow phenomena not only underscore the nonlinear nature of spectral interactions, but also suggest intriguing opportunities for sensing and control: for example the envelope effect shown in figure 2 could potentially be used to reconstruct the large-scale characteristics of the flow distant from the wall given short-time samples of the velocity close to the wall. In addition, control techniques targeted at the large scale structures, which can be correlated with the occurrence of high skin friction "sweep" events [1], may prove to be an important first step in relaxing stringent resolution requirements associated with control schemes designed to reduce skin friction.

In this paper, we review the recent experimental findings and explore the implications for modeling, computation and control of skin friction.

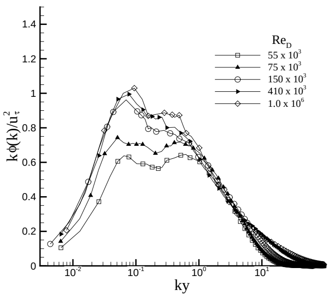

Figure 1: Spectral density of the streamwise turbulent fluctuations premultiplied by wavenumber at $y/R = 0.1$ in canonical smooth-wall pipe flow at a range of Reynolds number, Re_D.

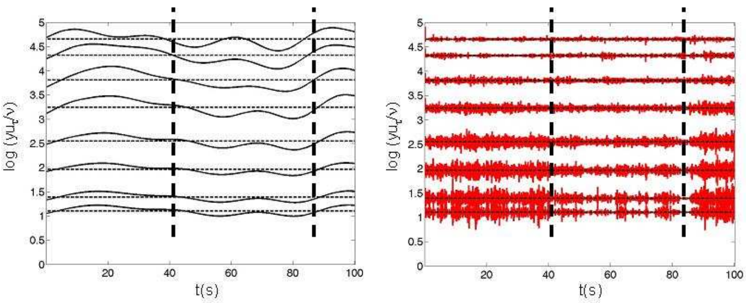

Figure 2: Simple filters on the simultaneous instantantaneous velocity traces across the near-wall layer in the near-neutral atmospheric surface layer: (left) low-pass filter at $f\delta U_{5m} = 0.5$ and (right) high-pass filter at $f\delta U_{5m} > 500$. Note how high intensity activity at high frequency correlates with negative low frequency excursions across the near-wall layer.

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